Recent MINOS results

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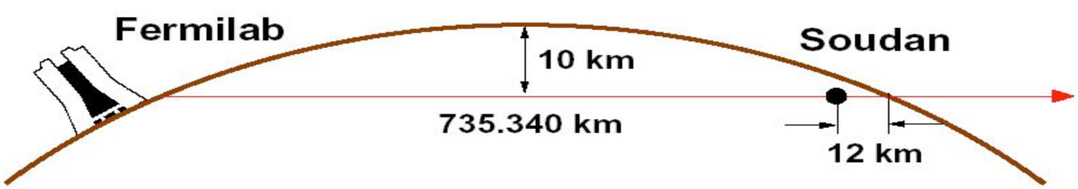
MINOS (Main Injector Neutrino Oscillation Search)

- Conventional muon neutrino beam from charged pion decays.
- Near detector is at 1.04 km from target (Fermilab) and far at 735 km (Minnesota).
- Measure spectra at near and far to search for muon neutrino disappearance or electron appearance.



Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab
Harvard • Holy Cross • IIT • Indiana • Minnesota-Twin Cities • Minnesota-Duluth • Otterbein
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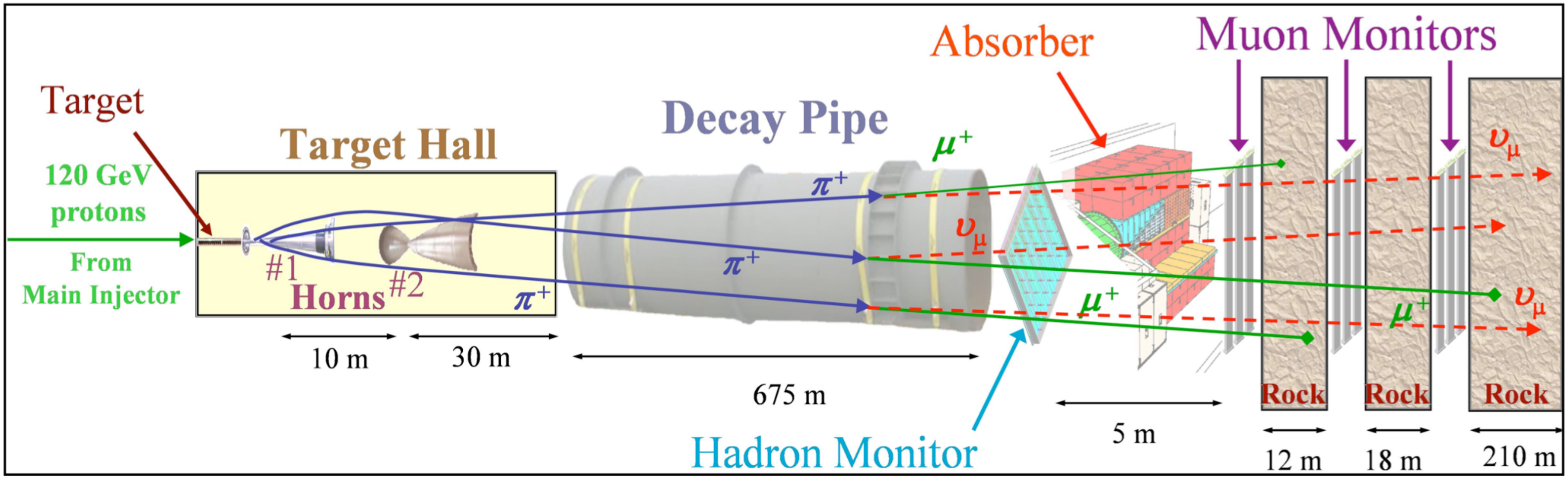
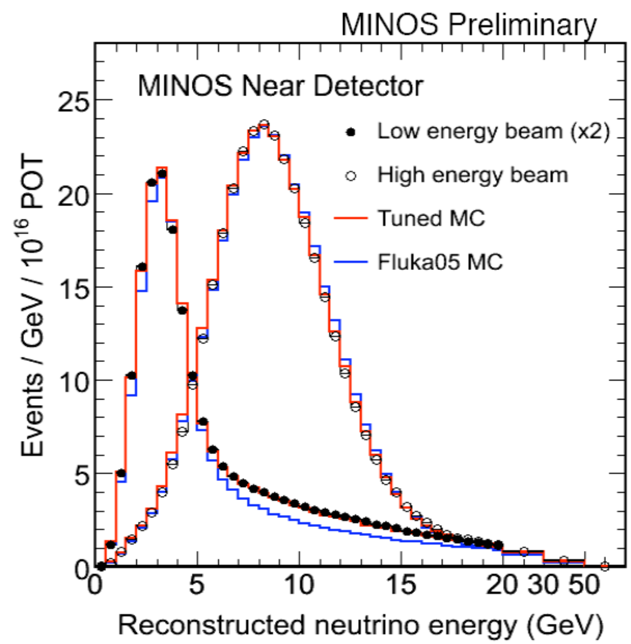
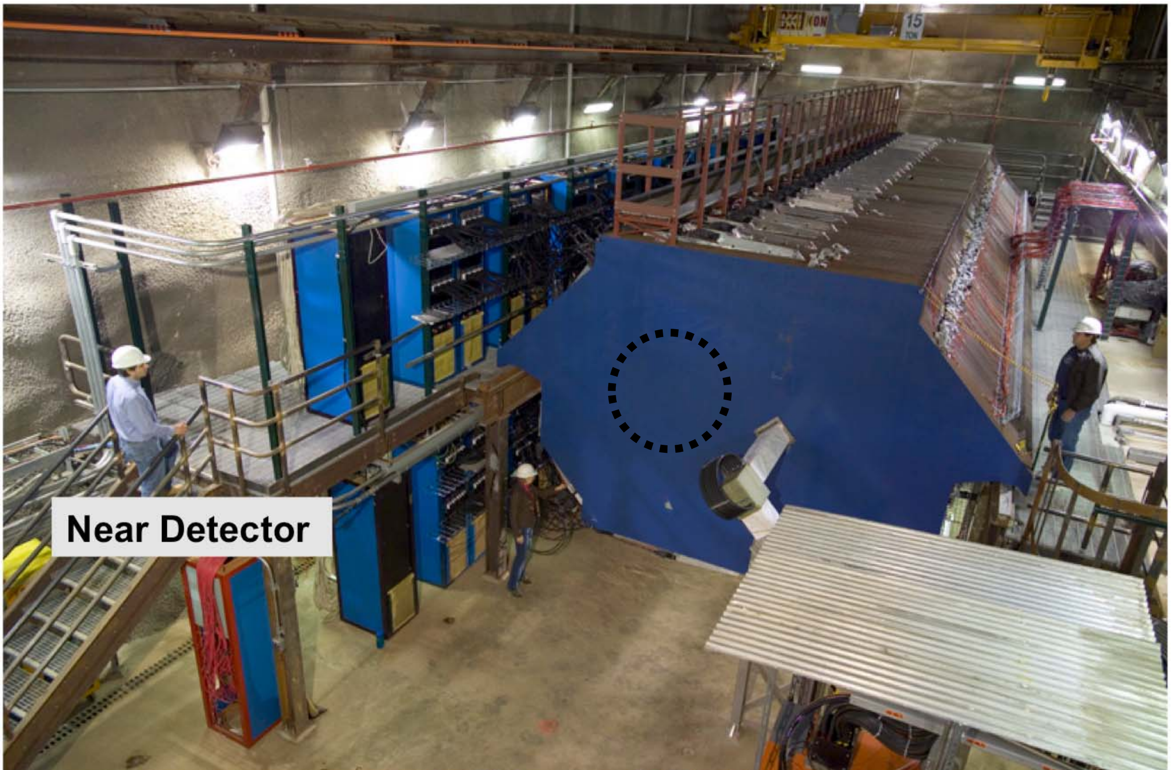
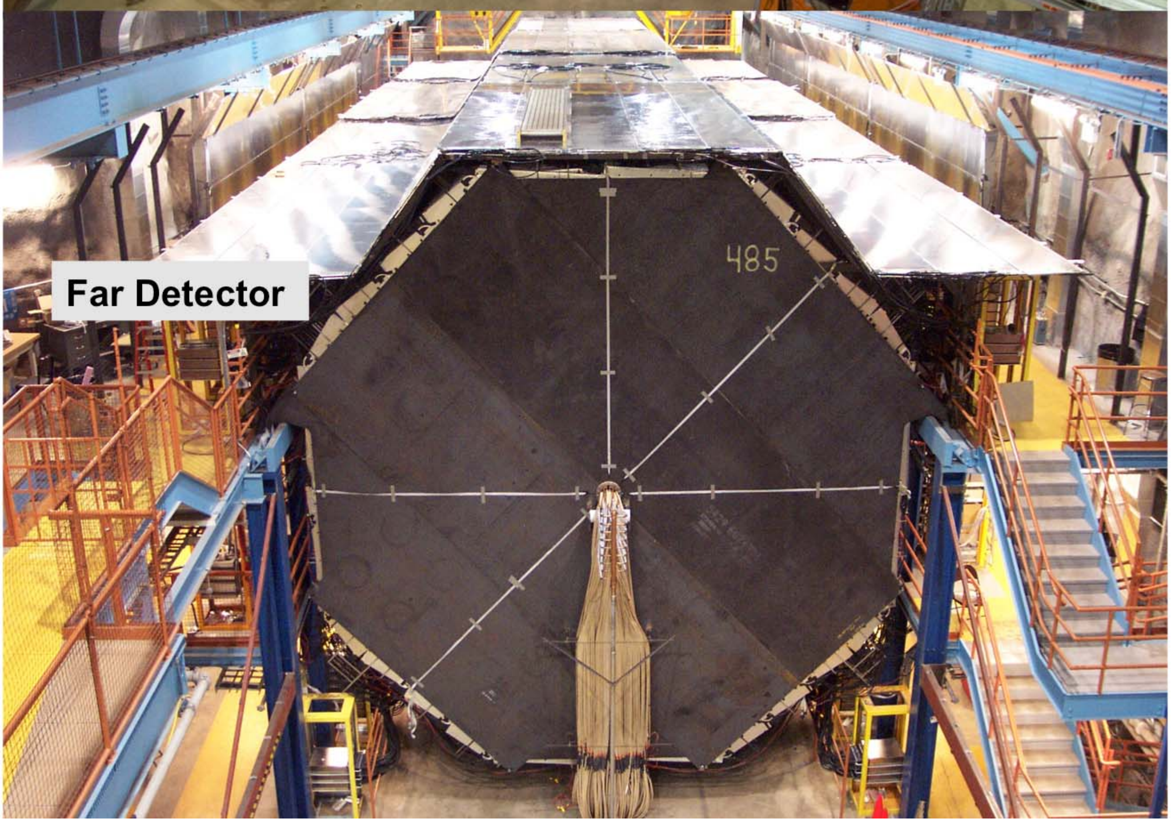
Horn focused muon neutrino beam



- 120 GeV protons from Main Injector
- Parabolic magnetic horns to sign select pions. Target can be moved to change beam energy.
- 10 μsec pulses/2.2 sec, 3.3×10^{13}protons/pulse
- Beam: ν_μ ~ 95%, anti-ν_μ~4%, ν_e~1.3%
- ν_μ and anti-ν_μ measured. ν_e constrained with tuned Monte Carlo.







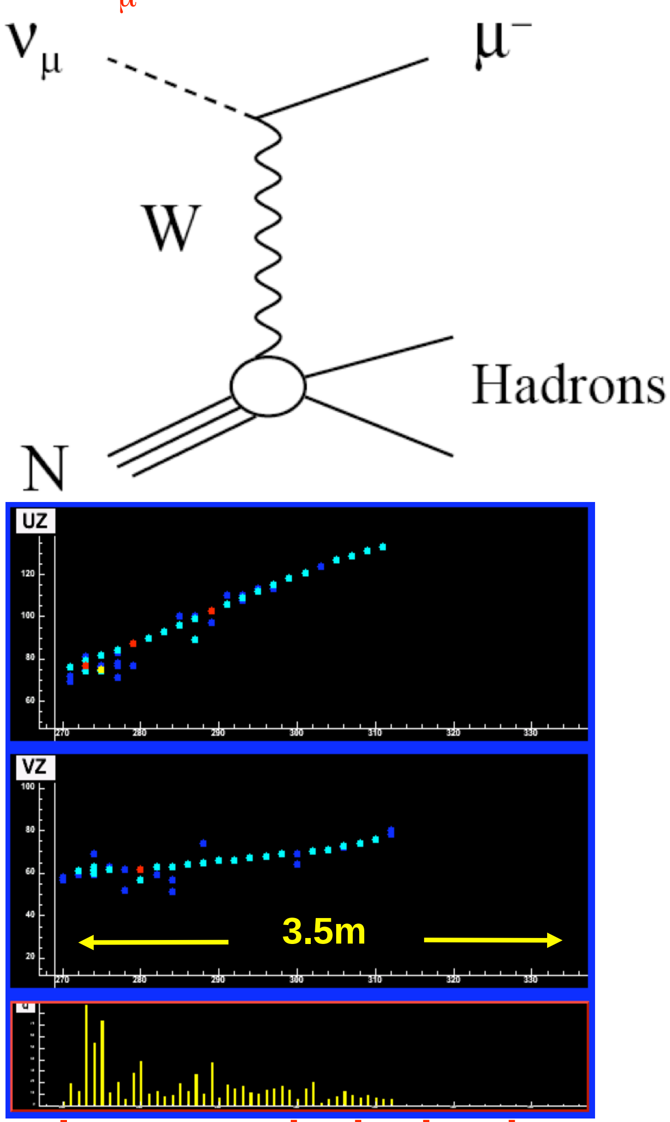
MINOS Detectors

- Massive
  - 1 kt Near detector (small fiducial)
  - 5.4 kt Far detector
- Similar as possible
  - steel planes
    - 2.5 cm thick
    - 1 Muon ~ 27 planes
    - 1.4 radiation lengths
  - scintillator strips
    - 1 cm thick
    - 4.1 cm wide
    - Molier radius ~3.7 cm

  - Wavelength shifting fibre optic readout
  - Multi-anode PMTs
  - Magnetised (~1.3 T)

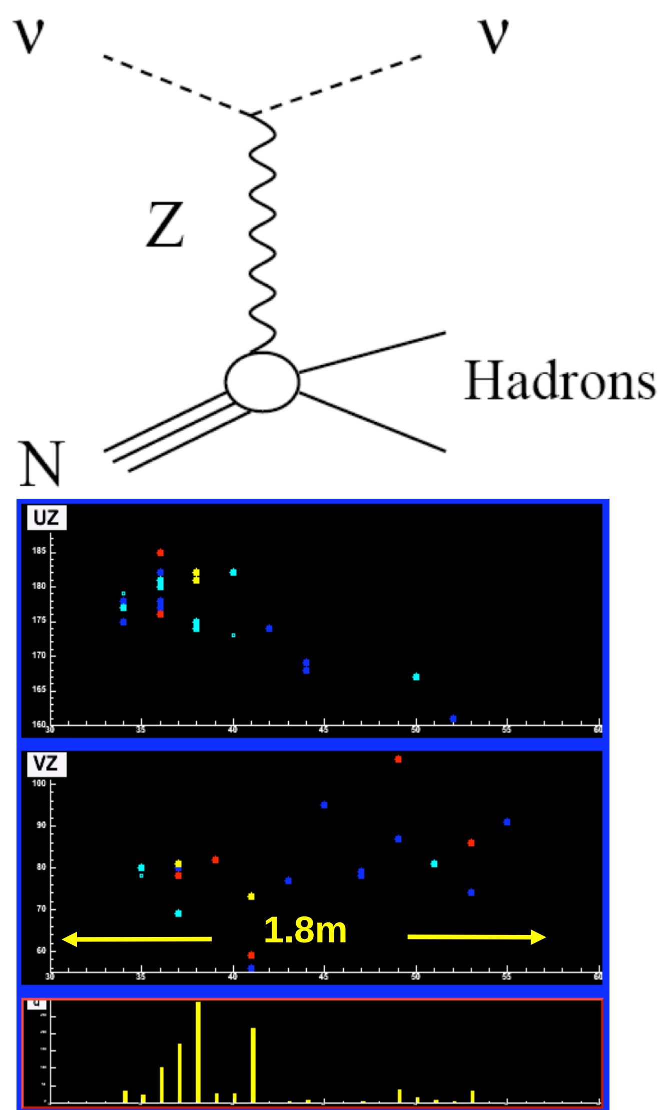
MINOS Event Topologies (MC)

ν_μCC Event



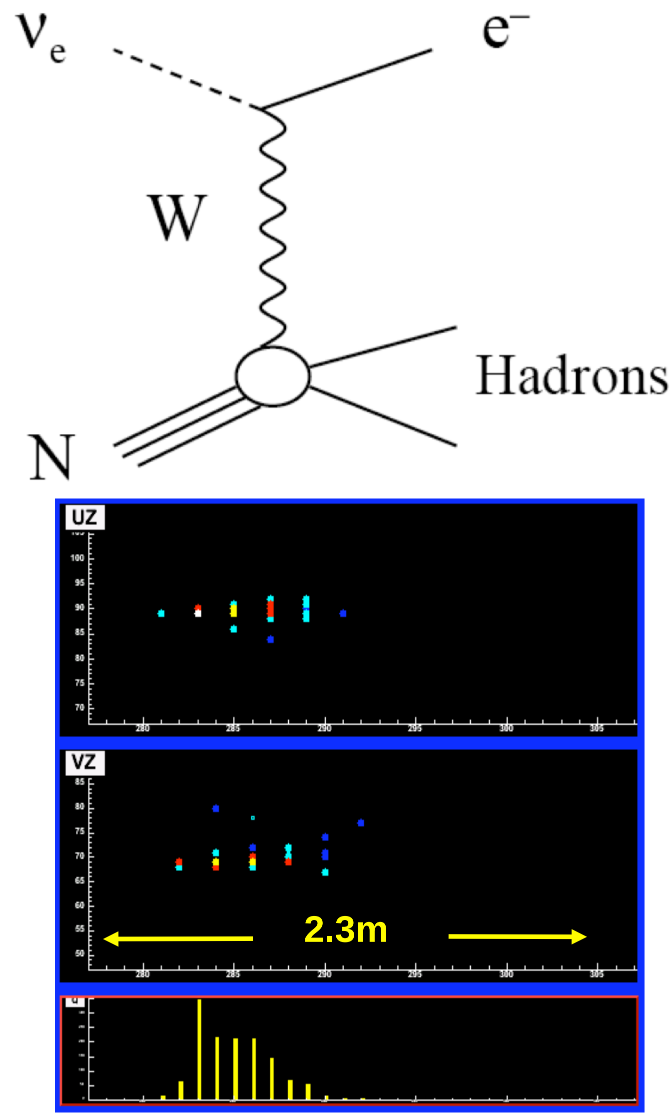
long μ track+ hadronic activity at vertex

NC Event



short event, often diffuse

ν_eCC Event



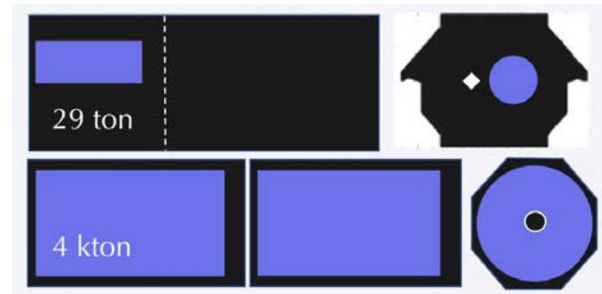
short, with typical EM shower profile

Analysis Challenge for ν_e

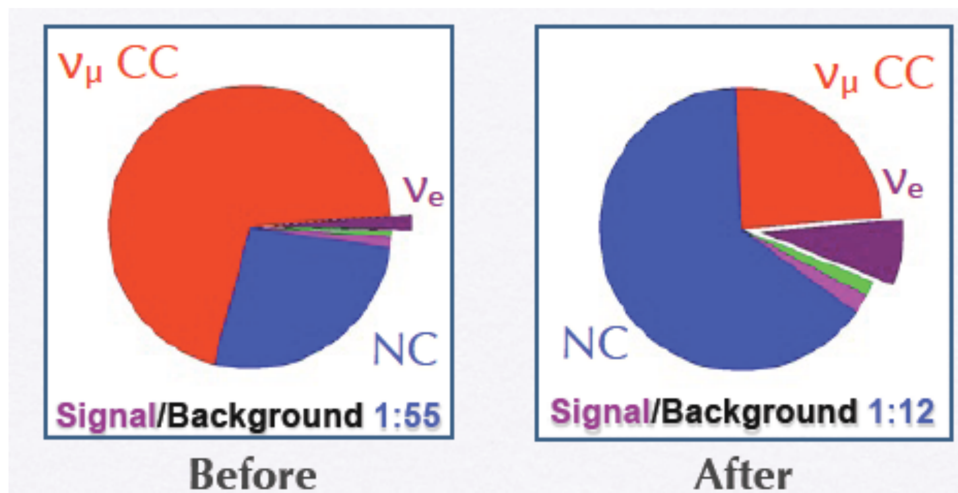
- Construct a selection algorithm to reject background and select ν_e
- Measure the background spectrum in the near detector.
- Use near detector measurement to predict far detector background.
- Minimize dependence on Monte Carlo.
- Carry out blind analysis. Check background estimates with independent samples.

Selecting ν_e events

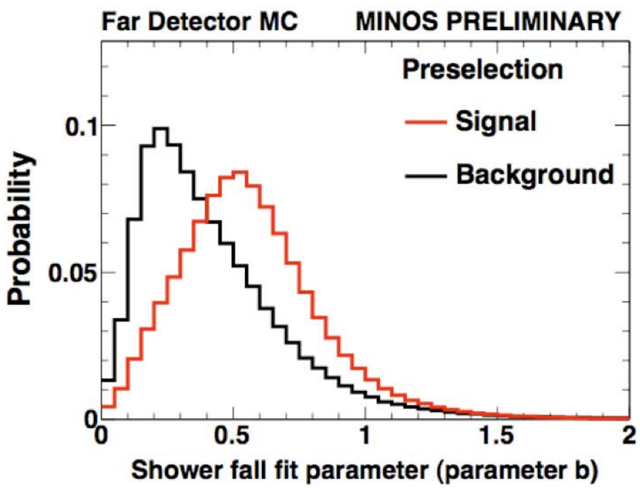
- **Basic cuts** to ensure data quality:
  - Beam quality and detector quality cuts.
  - Fiducial volume cuts:
  - Cosmic rejection cuts based on steepness.
- ν_e **preselection cuts** to reduce background.
- ν_e **selection cuts** based on shower topology

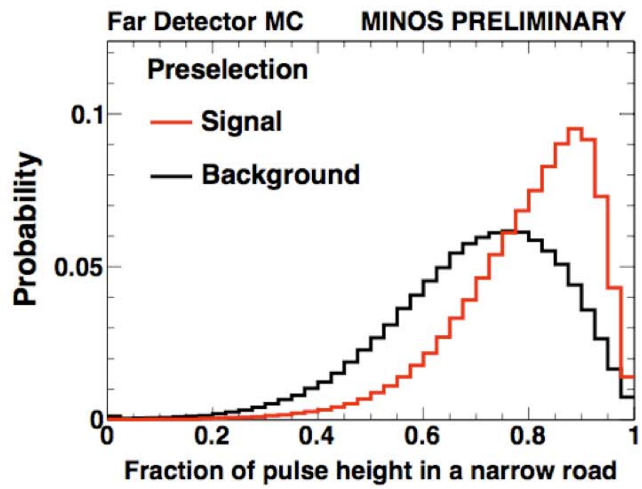


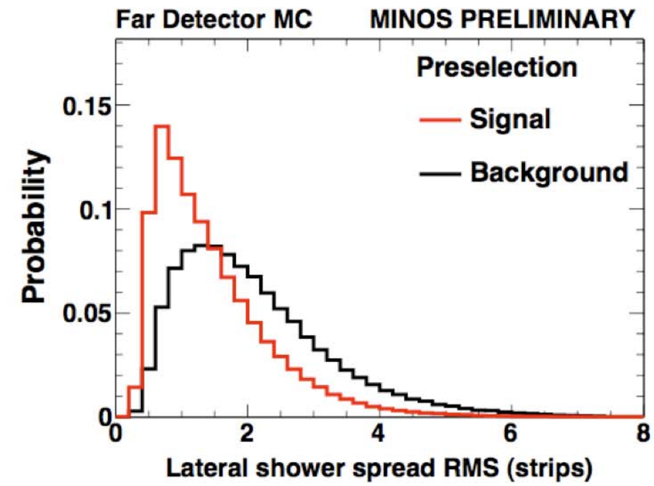
Preselection requirements:
Track length < 25 planes.
Track like length < 16 planes.
Reconstructed energy 1-8 GeV.
At least one shower and 4 contiguous planes with > 0.5 MIP energy units.



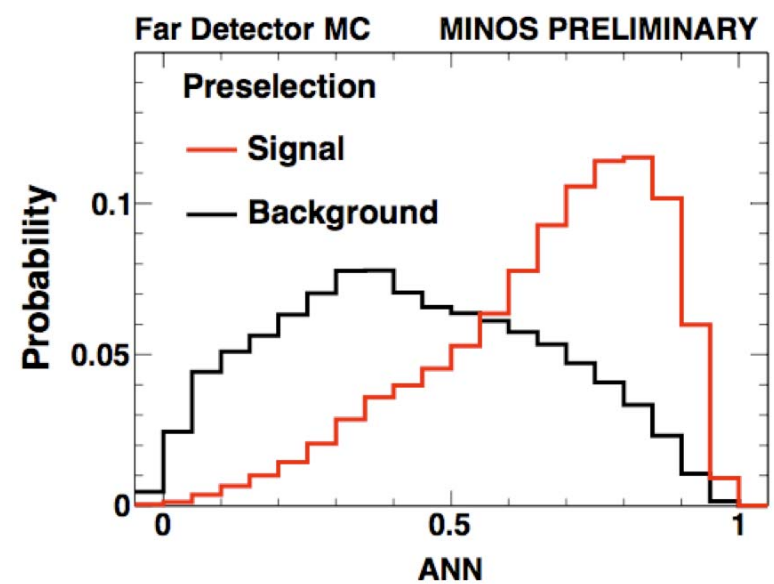
Selecting ν_e Events with Artificial Neural Net(ANN)







- 11 variables chosen describing length, width and shower shape
- ANN algorithm achieves:
  - signal efficiency 41%
  - NC rejection >92.3%
  - ν_μCC rejection >99.4%
  - signal/background 1:4 (chooz limit)

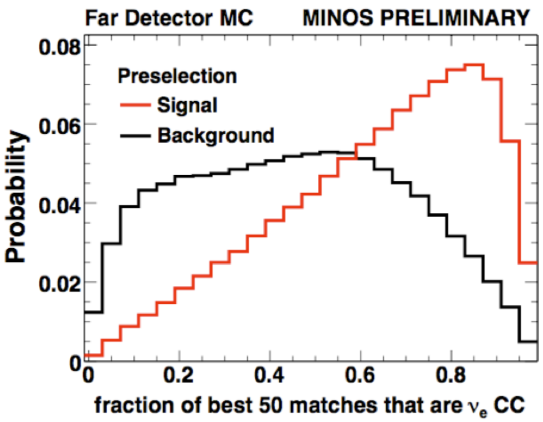


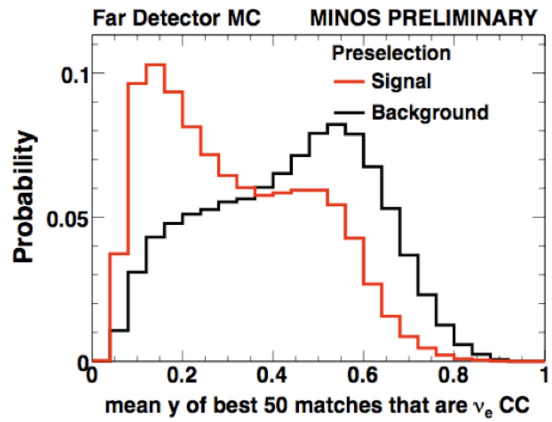
Primary method

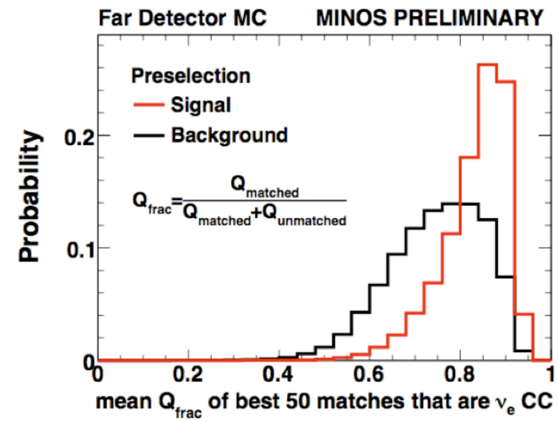
$\Delta m^2_{32}=0.0024\text{eV}^2$

Selecting ν_e events with Library Event Matching (LEM)

(fraction of electron neutrino events in 50 best matches)



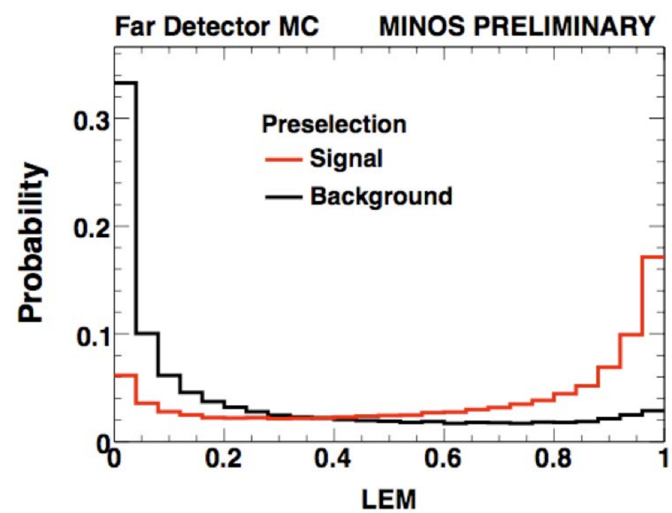




- Select 50 best matches according to the likelihood that two events have the same hit pattern in position and energy deposition. Use large MC library.
- Construct discriminant variables from the properties of the 50 best matches, eg. fraction of the 50 best matches that are ν_e CC.
- Build a likelihood from 3 variables as function of energy.

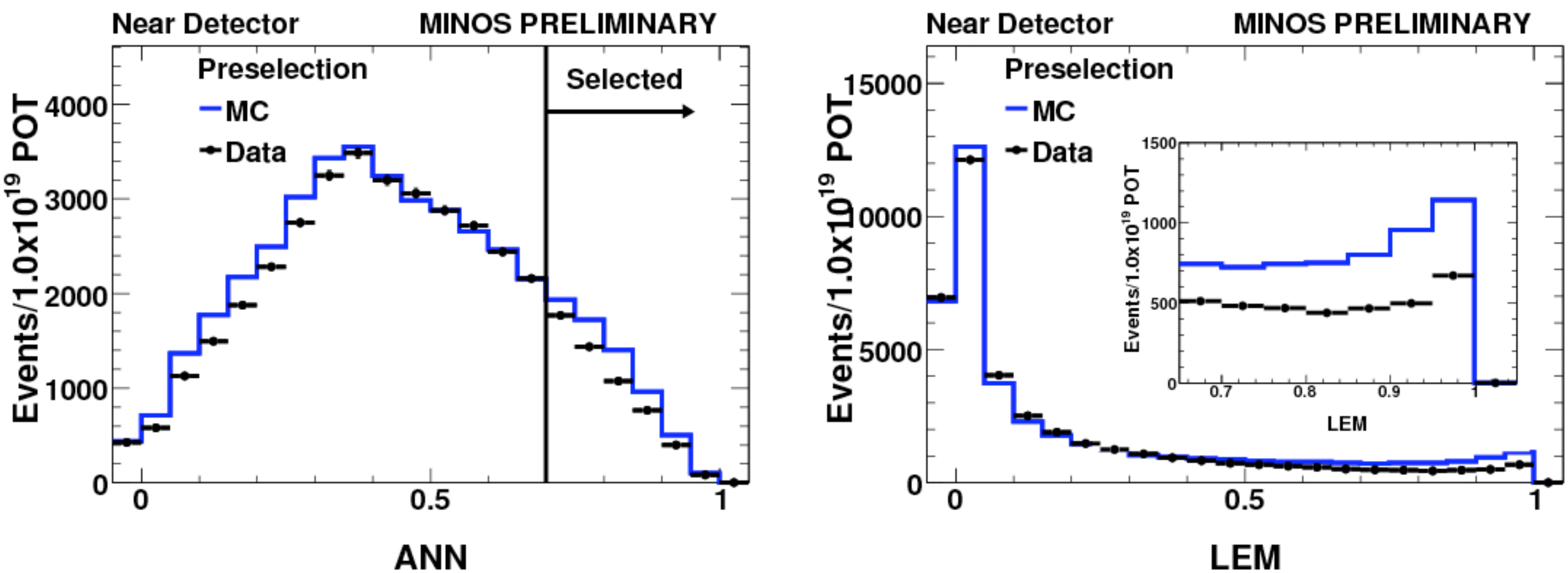
Secondary method
(systematics need checking)

With a cut of LEM>0.65:
signal efficiency 46%
NC rejection >92.9%
CC rejection >99.3%
signal/background 1:3



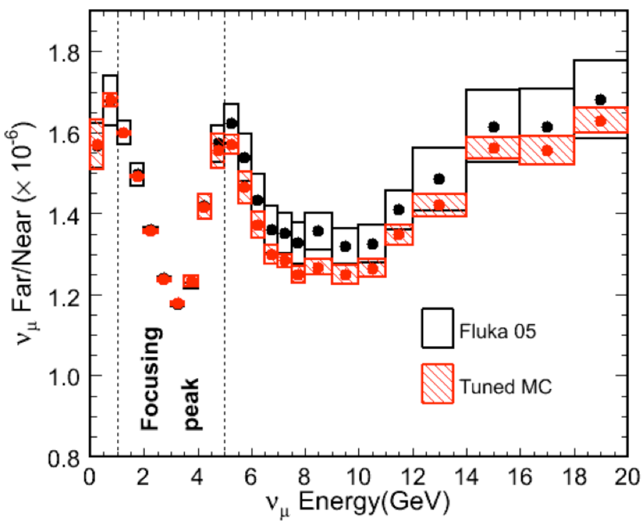
Δm^2_{32}=0.0024 eV^2,
$\sin^2\theta_{23}$=1.0

Near detector selection



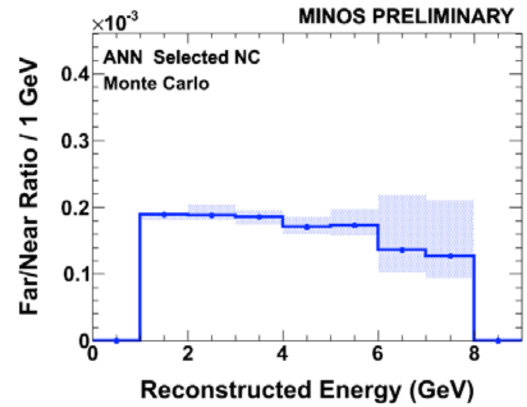
- ANN selected: 5524 events/10^{19} POT
- LEM selected: 3528 events/10^{19} POT
- Background is composed of CC (with invisible muons), NC, and νe contamination in the beam.
- MC does not model the absolute background well, but the CC/NC ratios have better control. Contamination well modeled.
- We also use ν_μ charged current data with muon removed to check our background calculation.

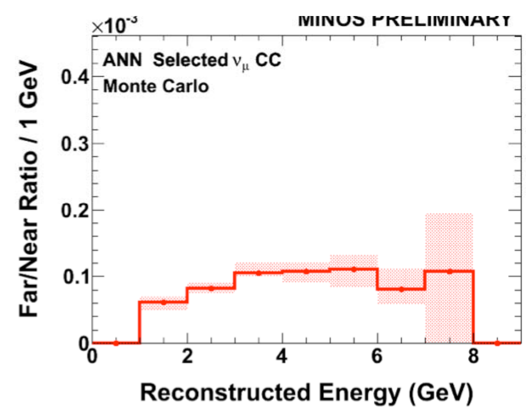
Extrapolating background to FAR



Beam extrapolation

- MC used to correct
- Fiducial mass
- Energy smearing
- CC oscillation
- PID efficiency for
- detector diff.
  - Fibers
  - readout
  - light level
  - gain calibration
  - cross talk, etc.





similar for LEM

ANN far $\simeq$ 5524 (near) X 1.3 10^{-6} X 4000 ton/29 ton X 3.14 10^{20} POT /10^{19}POT

$\simeq$ 31 events => further corrections => 27

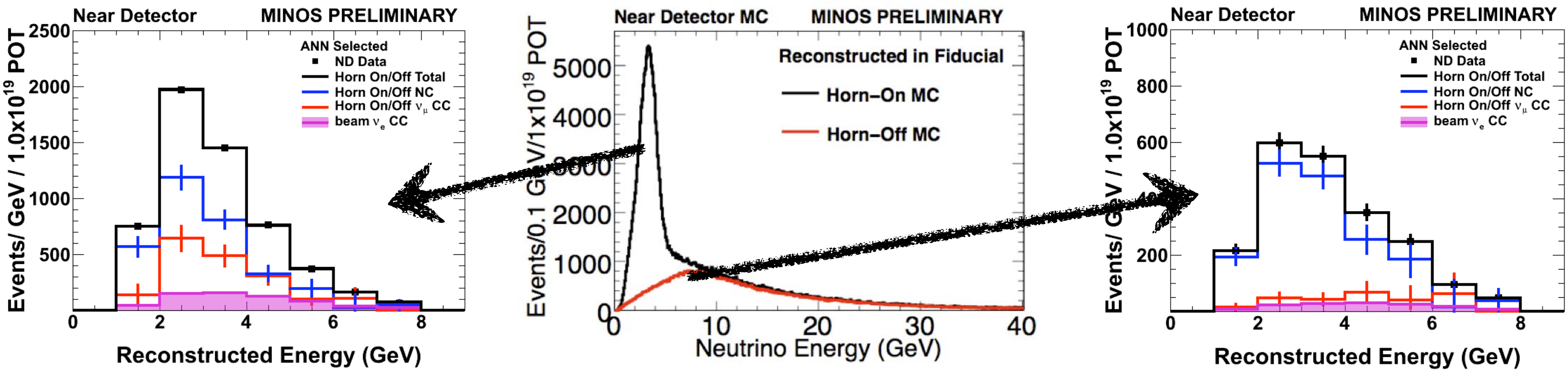
LEM far $\simeq$ 3528 (near) X 1.3 10^{-6} X 4000 ton/29 ton X 3.14 10^{20} POT /10^{19}POT

$\simeq$ 20 events => further corrections => 22

To get more accurate answers need to separate CC (with invis. muons) and NC backgrounds, use spectrum and account for detector differences.

CC/NC separation

5524 evts



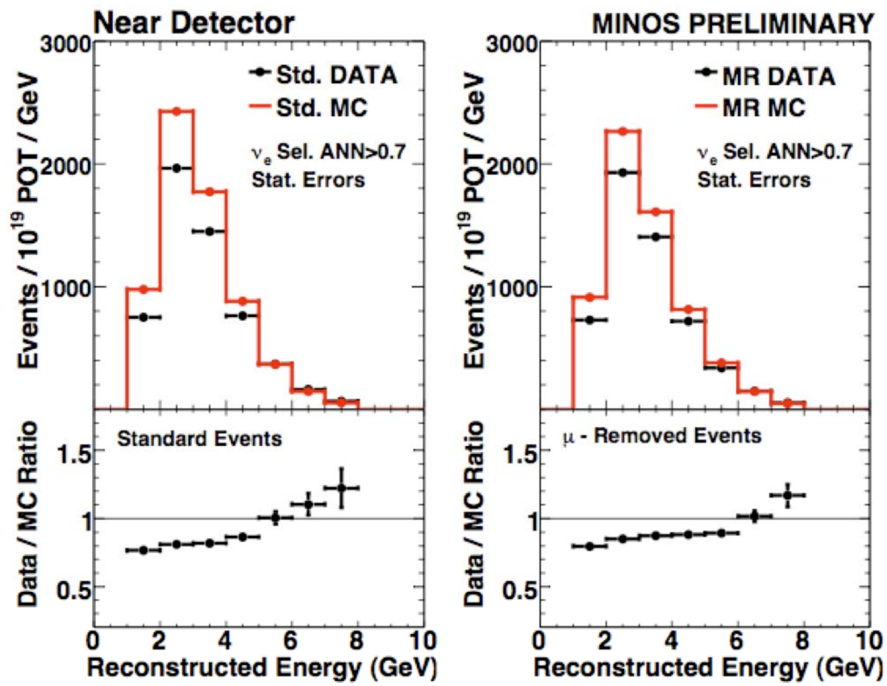
Horn on spectrum has both CC NC contributions

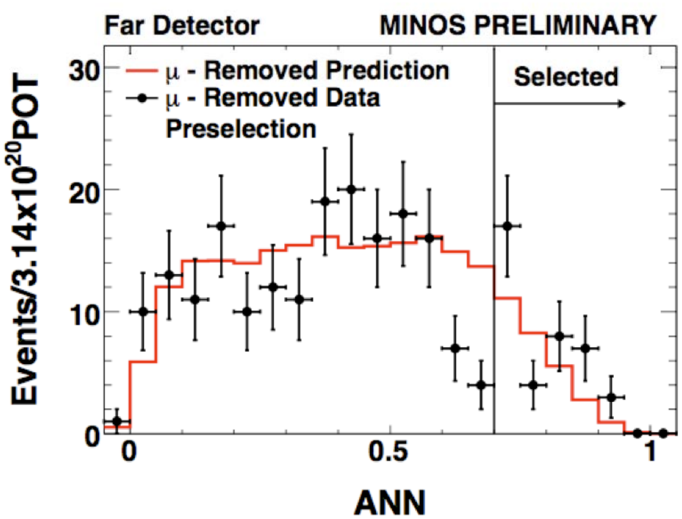
Horn off has mainly NC because CC have longer muons and get rejected

- Minimize dependence on MC by utilizing data with horn/off spectrum
- Calculate the CC/NC fractions using MC input: ratios of CC/NC for Hon and Hoff and the beam contamination ν_e in reco. energy bins.
- Statistical error from Hoff data, systematics from how well ratios are known and stable against cuts.
- Final backg numbers are: 27+- 5+-2 for ANN, and 22+-5+-3 for LEM, errors dominated by modeling of detector differences.

Muon removed showers from CC

- Allows two checks
  - Independent background calculation.
  - Complete check of analysis by looking at far events without looking at signal.





ANN (Primary):

observe 39 events
expect 29 +- 5(stat) +- 2(syst)

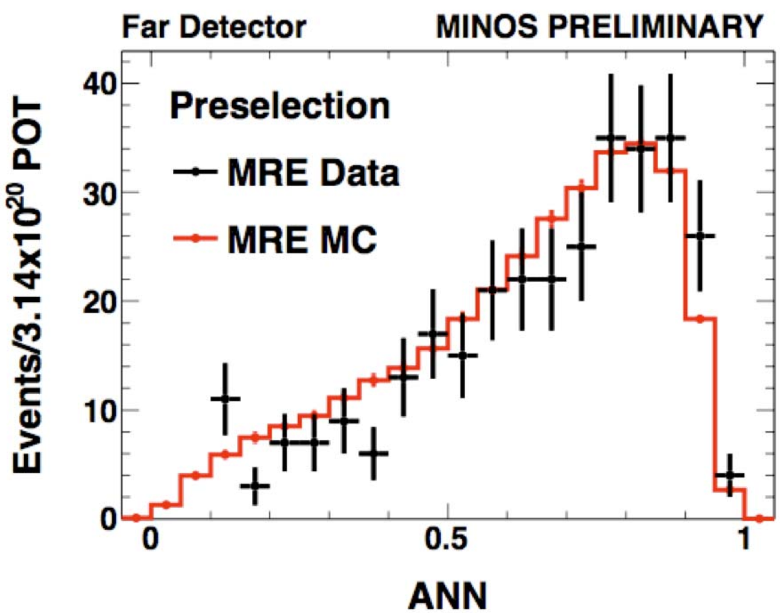
discrepancy between MRCC data and MC is very similar to the discrepancy in standard data and MC, both in shower shape and energy. We can correct the MC by this discrepancy.

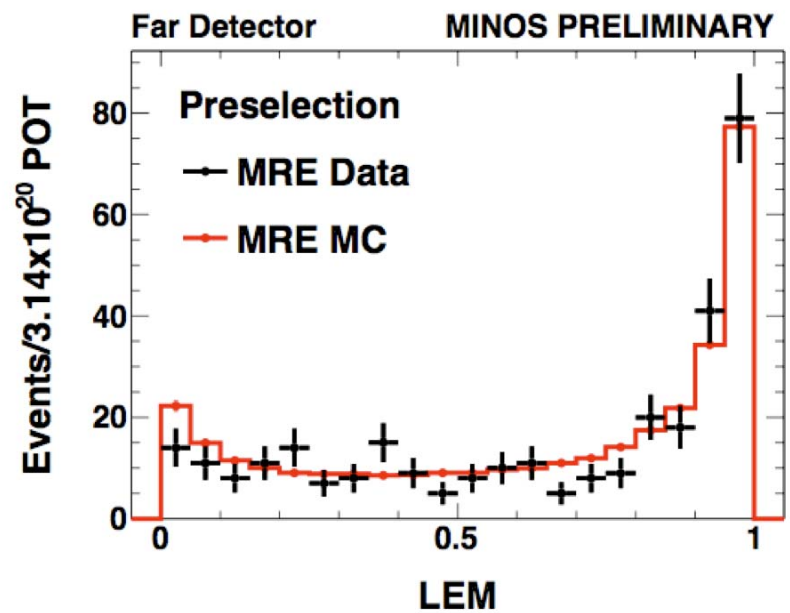
	Total	NC	ν_μ CC	ν_τ CC	ν_e beam
Horn on/off	**27**	**18.2**	**5.1**	**1.1**	**2.2**
MRCC	28	21.1	3.6		

Two methods agree

Muon removed electron added

- Adding the electron to the muon removed events, present good agreement in PID.
- Verification of signal selection efficiency.





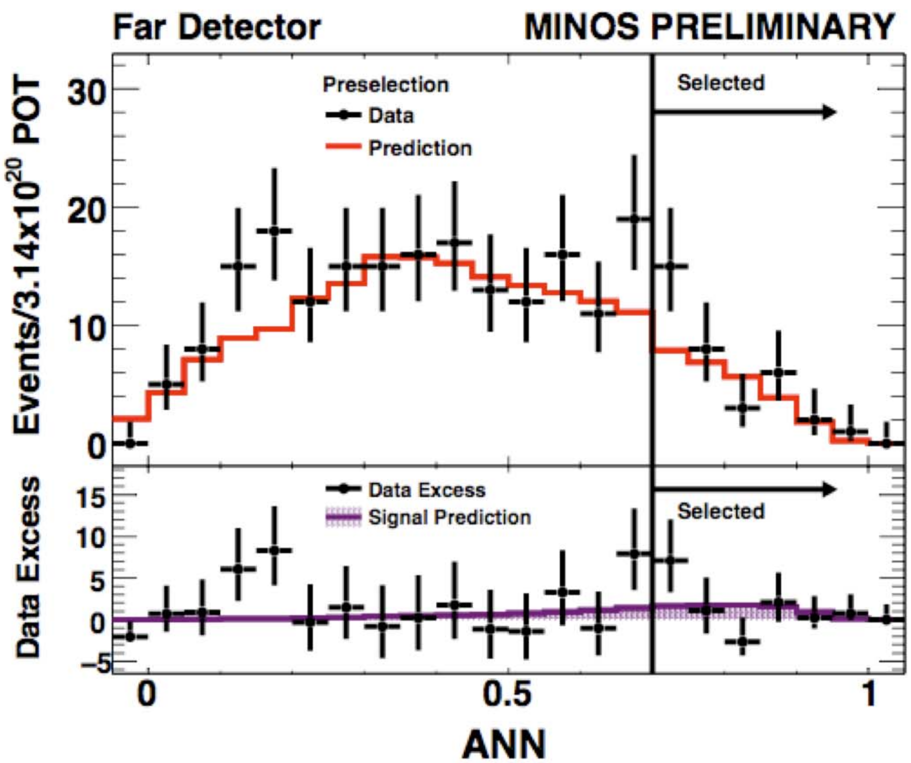
- **We observe a total of 159 events.**
- **We expect 152±13(stat)±12(sys) events.**

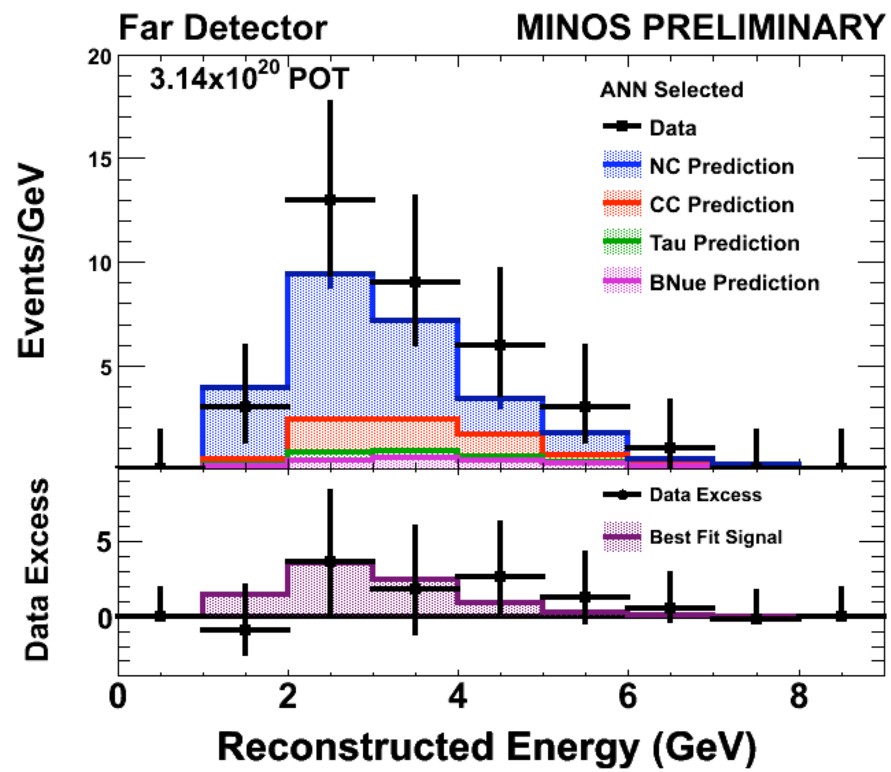
- We observe a total of 180 events.
- We expect 176±13(stat)±16(sys) events.

We model the signal well.
At Chooz limit expectation is 6-12 events depending on the value of the CP phase.

Signal region examination (1)

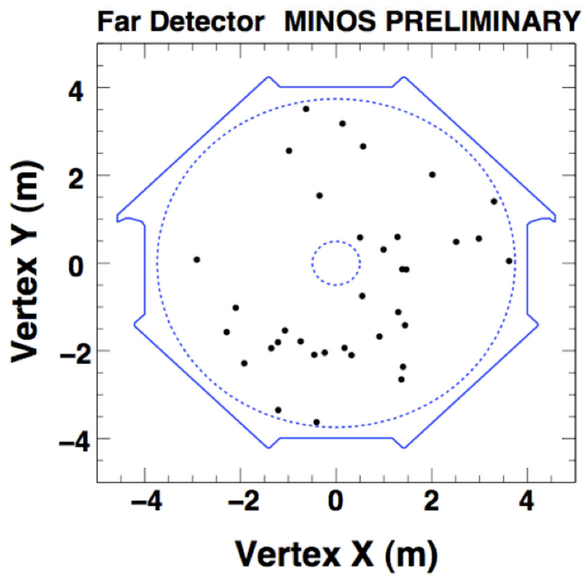
ANN (Primary Selection Method)

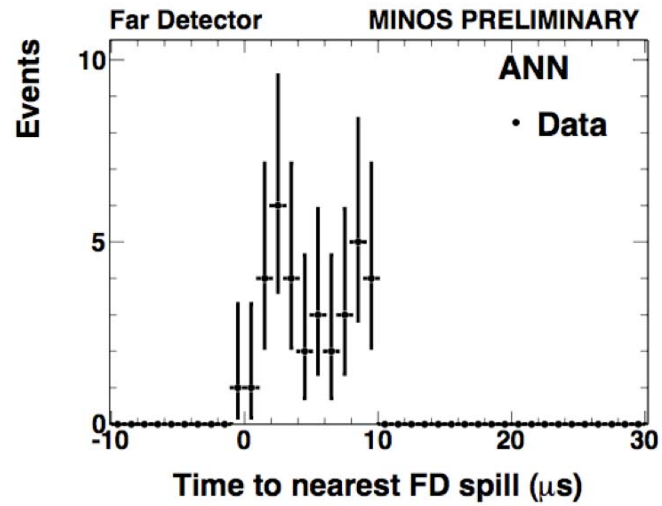


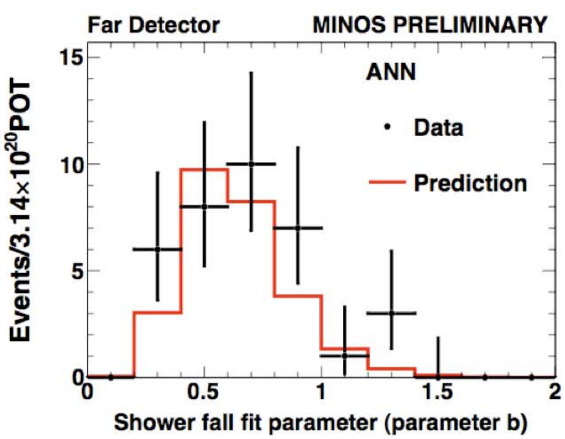


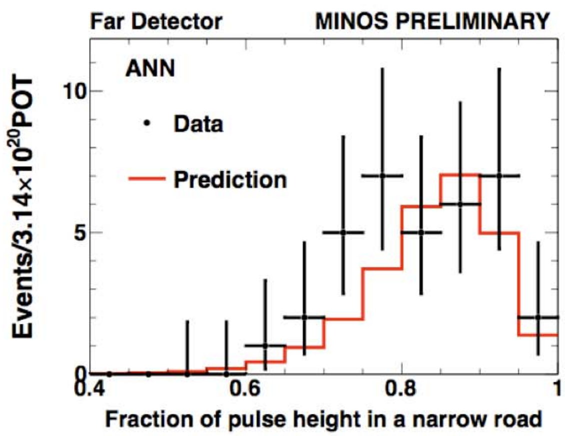
Observation: 35 events
Expected Background: 27 +- 5(stat) +- 2(syst) events

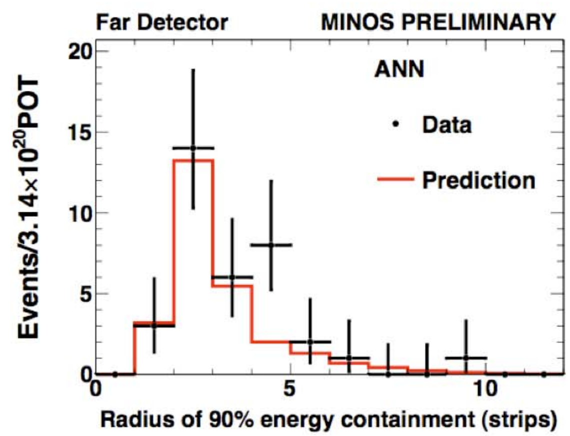
Far Data Distributions





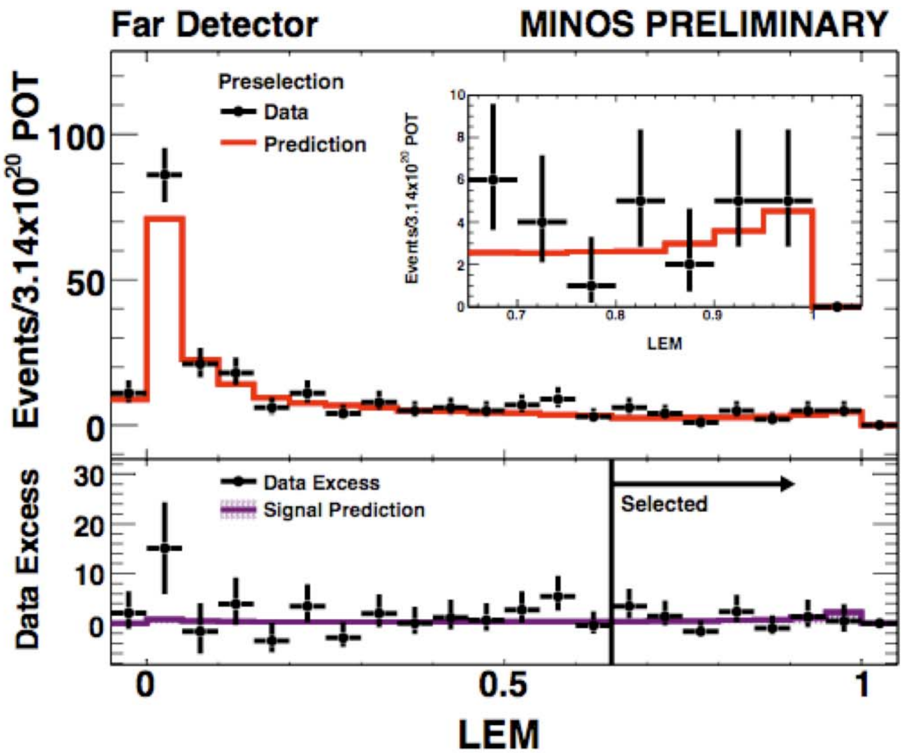


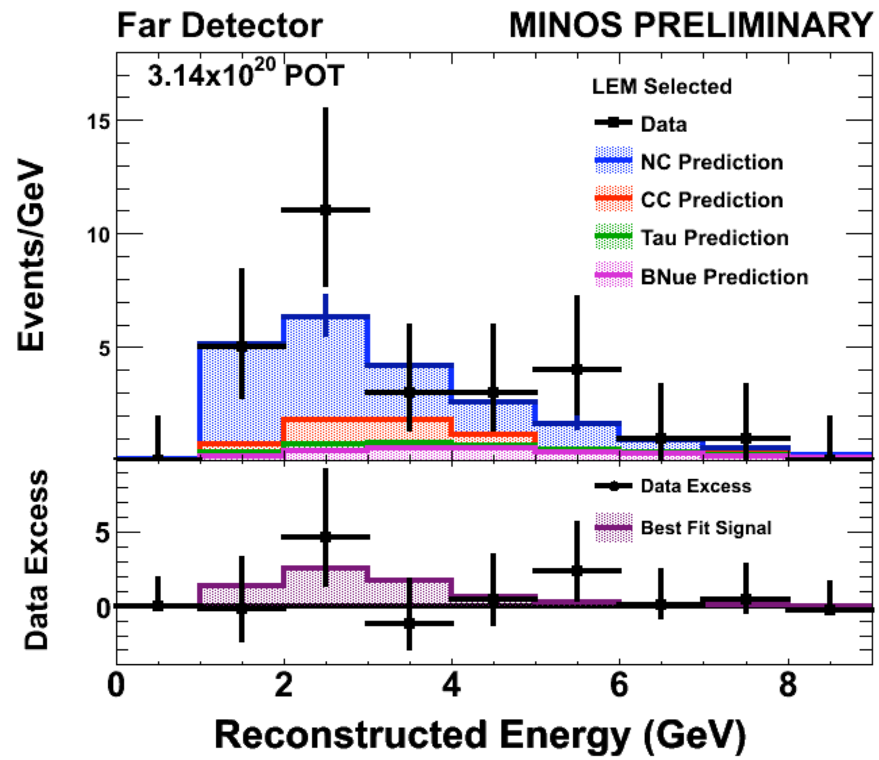




Signal region examination (2)

LEM (Secondary Selection Method)

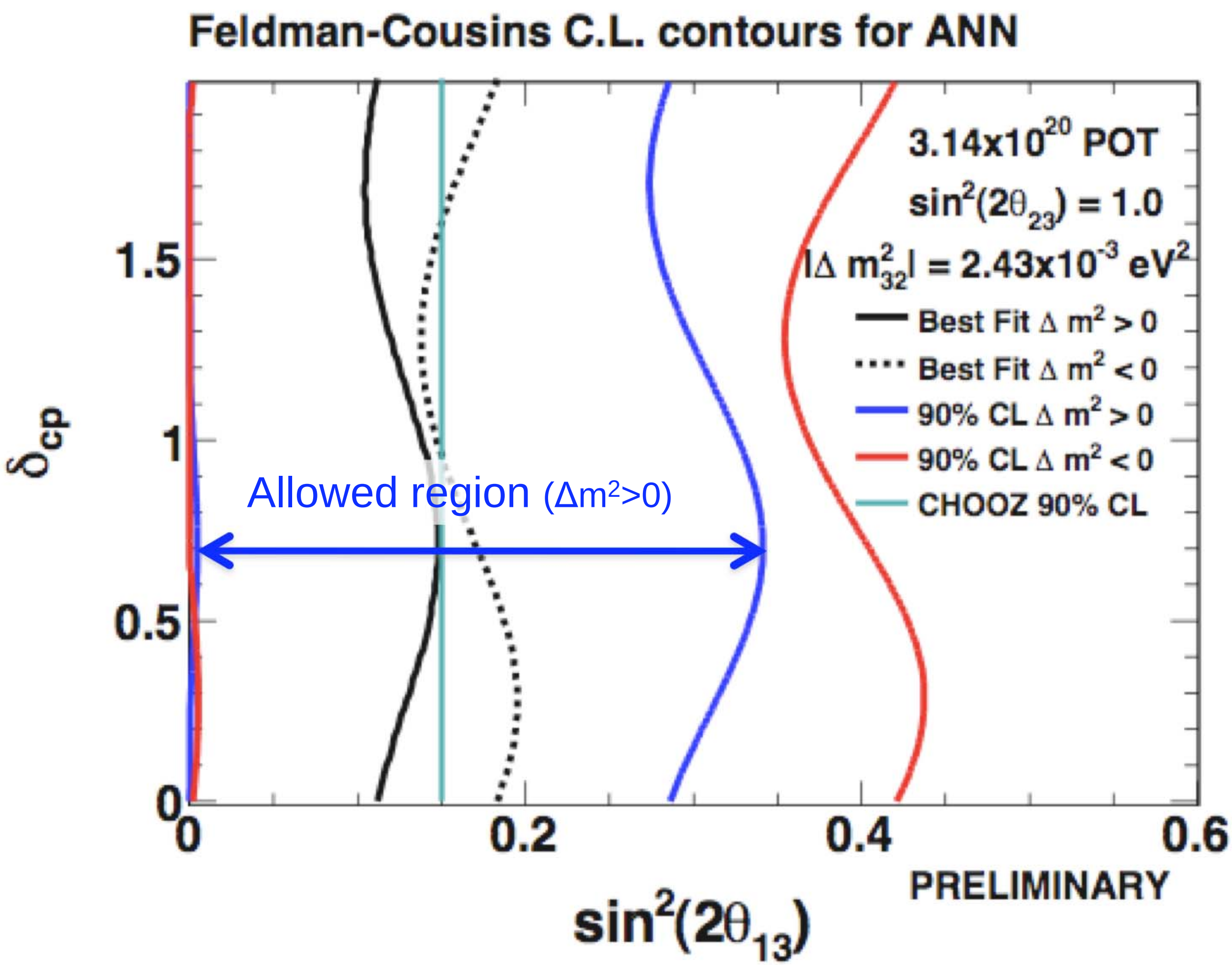




Observation: 28 events
Expected Background: 22 +- 5(stat) +- 3(syst) events

Allowed Region

- A Feldman-Cousins method was used
- Fit simply to the number of events from 1-8 GeV, no shape or correlation information used.
- Best fit and 90% C.L. limits are shown:
  - for both mass hierarchies
  - at MINOS best fit value for Δm^2_{32} & $\sin^2(2\theta_{23})$



- **Results:**

Normal hierarchy (δ_{CP}=0):

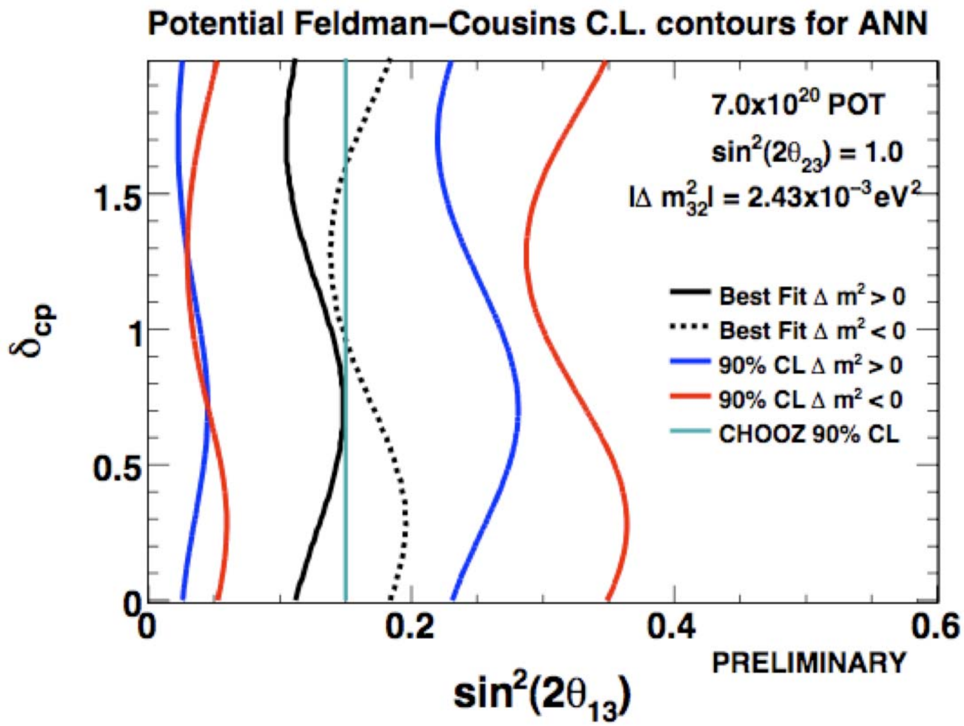
$\sin^2(2\theta_{13}) < 0.29$ (90% C.L.)

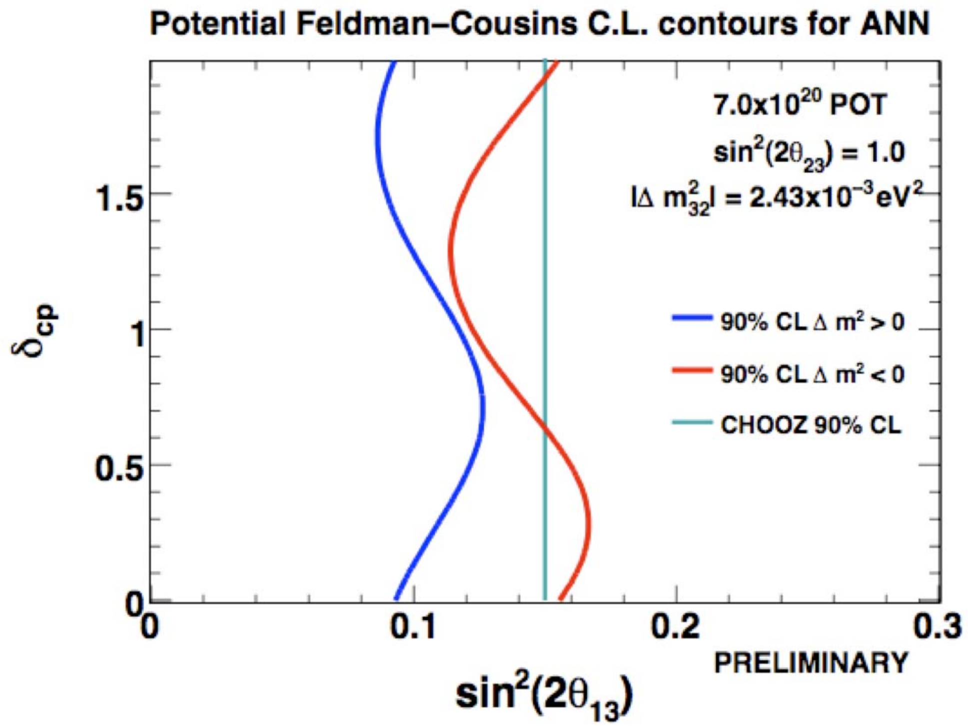
Inverted hierarchy (δ_{CP}=0):

$\sin^2(2\theta_{13}) < 0.42$ (90% C.L.)

Future 90% CL contours

7.0 x10^{20} POT





Future measurement if data excess persists.

Future limit if excess cancels with more data.

We have already doubled the data set.

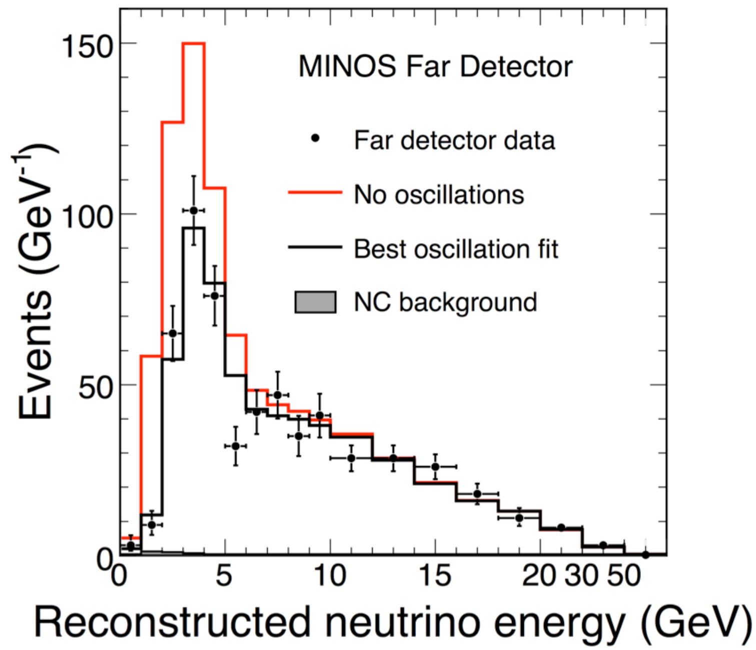
Far Detector ν_μ CC Data

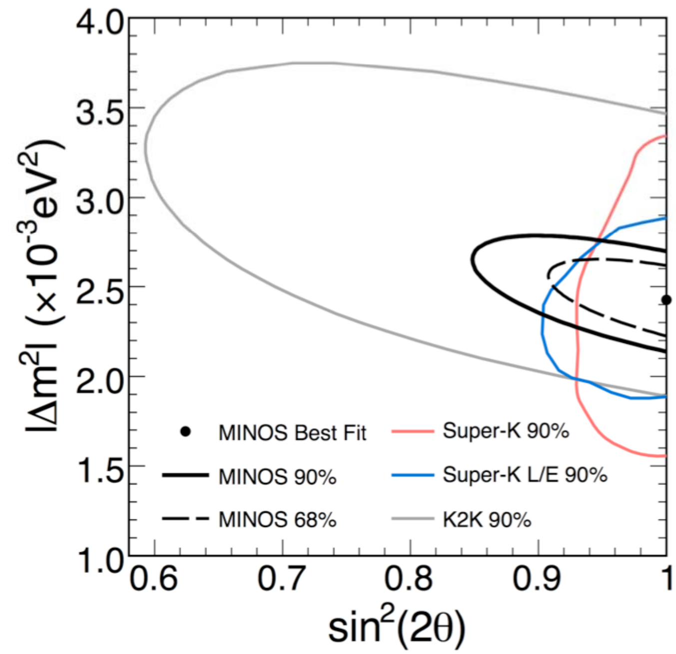
- See strong energy dependent distortion of spectrum
- Prediction using near detector data.
- Energy spectrum fit with the oscillation hypothesis:

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

$|\Delta m^2_{32}|=(2.43\pm0.13)\times10^{-3}\ \mathrm{eV}^2$
at 68% C.L.

$\sin^2(2\theta_{23}) > 0.90$
at 90% C.L.





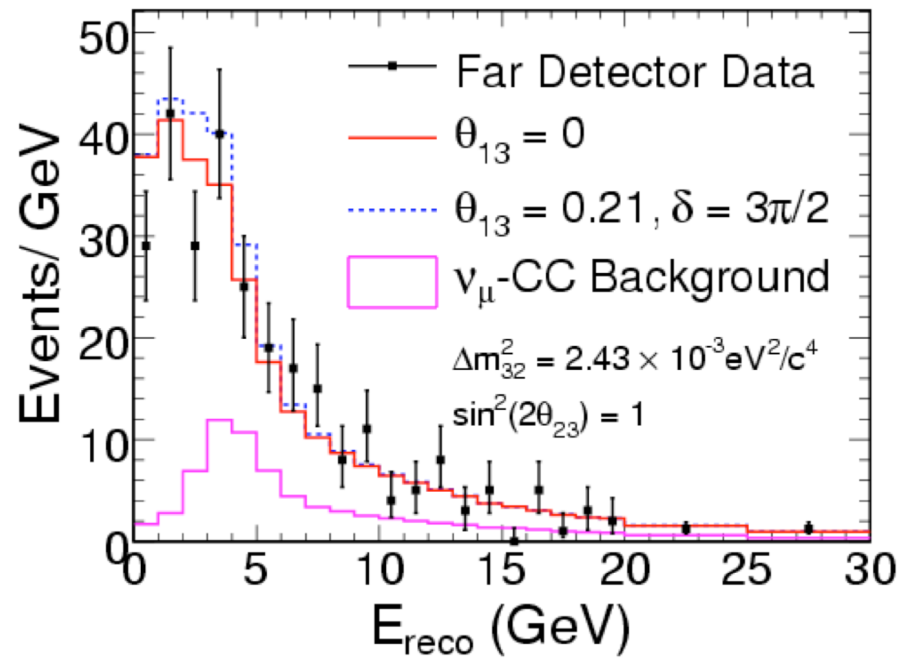
Neutral Current Analysis

- General NC analysis overview:
  - All active neutrino flavours participate in NC interaction
  - Mixing to a sterile-ν will cause a deficit of NC events in Far Det.
  - Assume one sterile neutrino and that mixing between ν_μ, ν_s and ν_τ occurs at a single Δm^2
- Survival and sterile oscillation probabilities become:

$$P(\nu_\mu - \nu_\mu) = 1 - \alpha_\mu \sin^2(1.27\Delta m^2 L/E)$$

$$P(\nu_\mu - \nu_s) = \alpha_s \sin^2(1.27\Delta m^2 L/E)$$

- ($\alpha_{\mu,s}$ = mixing fractions)



Simultaneous fit to CC and NC energy spectra yields the fraction of ν_μ that oscillate to ν_s:

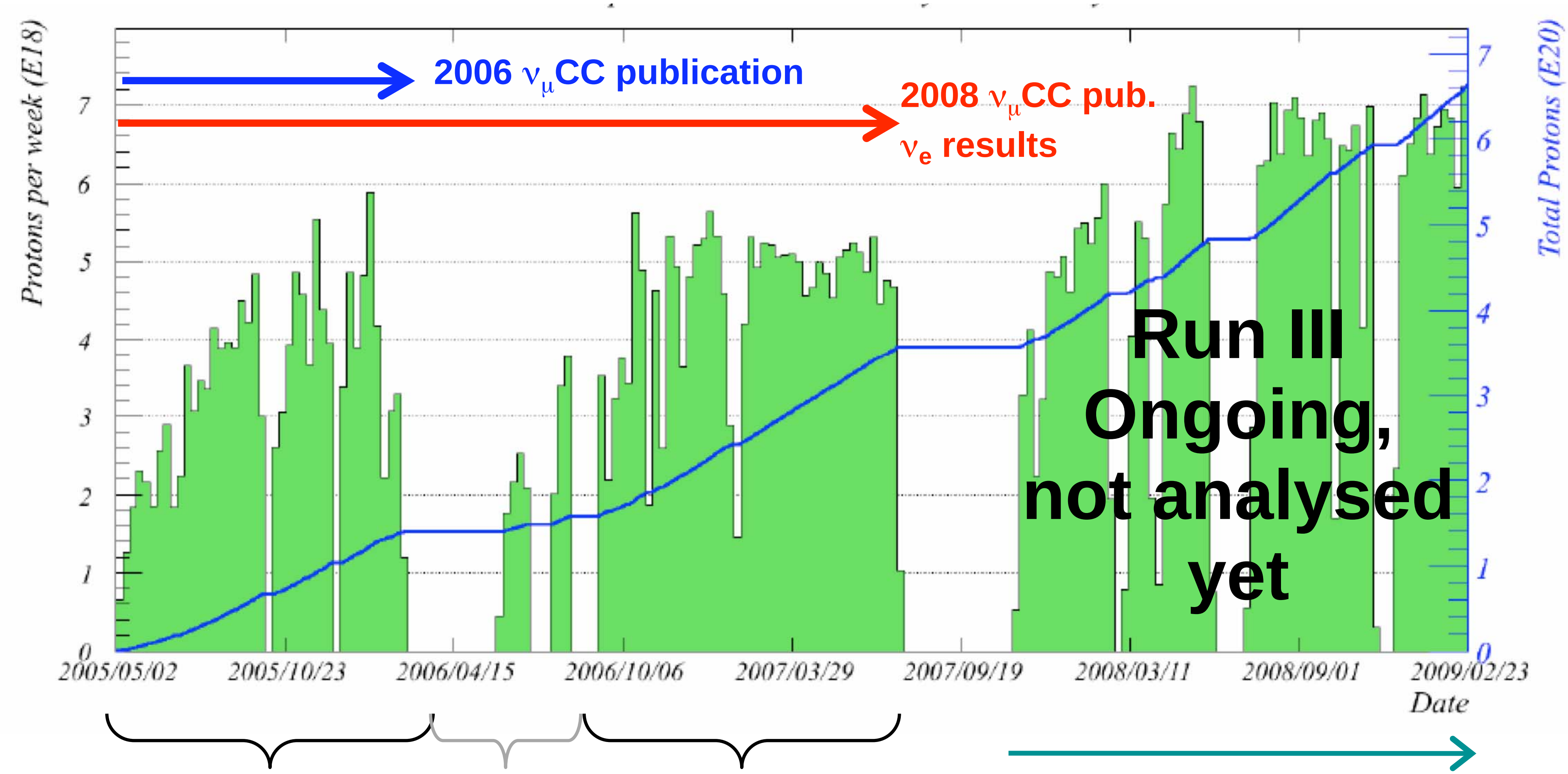
$$f_s = \frac{P(\nu_\mu \to \nu_s)}{1 - P(\nu_\mu \to \nu_\mu)} = 0.28^{+0.25}_{-0.28}(\text{stat.+syst.})$$

$$\boxed{f_s < 0.68 \quad (90\%\ \text{C.L.})}$$

Conclusion

- MINOS has analysed 3.2×10^{20} POT of beam data (>6.6×10^{20} POT data now taken)
- Muon neutrino disappearance
  - $|\Delta m^2_{32}| = (2.43\pm0.13)\times10^{-3}\ \mathrm{eV}^2$ (68% C.L.)
  - $\sin^2(2\theta_{23}) > 0.90$ (90% C.L.)
- Search for sterile neutrino mixing fraction
  - $f_s < 0.68$ (90% C.L.)
- Search for electron neutrino appearance
  - $\sin^2(2\theta_{13}) < 0.29$ (90% C.L.) (for normal mass hierarchy, $\delta_{CP}=0$)
- Prospects are good for pushing below Chooz limit with improved analysis techniques and more data.

Accumulated Beam Data



RUN I

1.27×10^{20} POT

Higher energy beam

0.15×10^{20} POT

RUN II

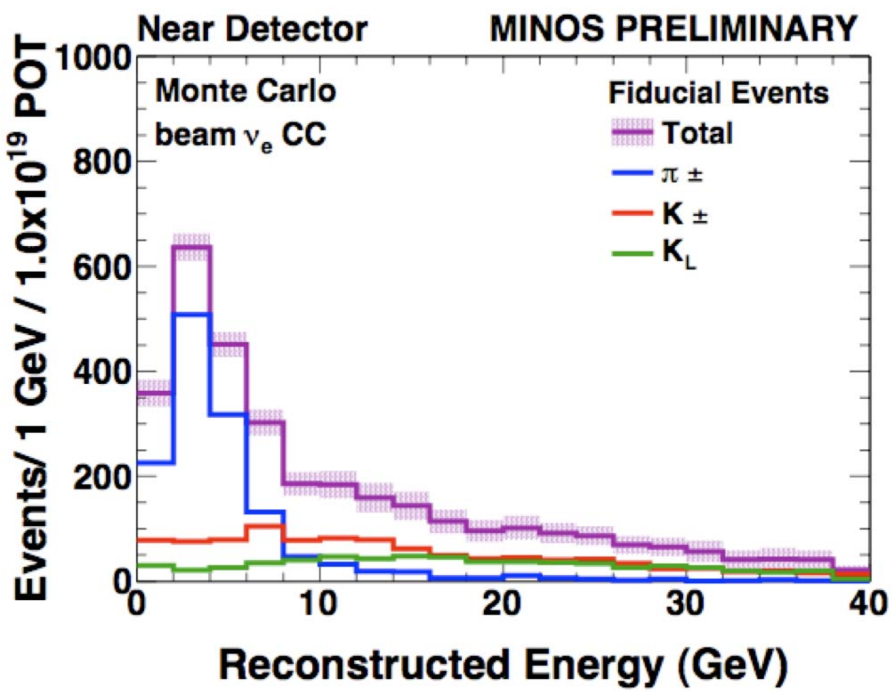
1.87×10^{20} POT

RUN III

$>3 \times 10^{20}$ POT

Beam ν_e component

- Neutrino beam has 1.3% of ν_e contamination from pion and kaon decays.
- Region of interest for the ν_e oscillation analysis, 1-8GeV, dominated by events from secondary muon decays:
- $$\begin{aligned} \pi^+ \quad \rightarrow \quad & \mu^+ \nu_\mu \\ & \hookrightarrow e^+ \bar{\nu}_\mu \nu_e \end{aligned}$$
- Near and Far beam ν_e spectra are constrained by using ν_μ events from several beam configurations.



Uncertainties on the flux in the region of interest are ~10%.